# Laboratory Measurements of Multi-Frequency and Broadband Acoustic Scattering from Turbulent and Double-Diffusive Microstructure

Andone C. Lavery
Applied Ocean Physics and Engineering Department
Woods Hole Oceanographic Institution
Bigelow 211, MS #11
Woods Hole, MA 02543
telephone: (508) 289-2345 fax: (508) 457-2194 email: alavery@whoi.edu

Grant Number: N00014-02-10359

## LONG-TERM GOALS

The long-term goal of the proposed research is to develop a fundamental understanding of high-frequency acoustic scattering from small-scale physical processes that occur in the ocean interior.

## OBJECTIVES

The primary scientific objective of the proposed research is to measure, characterize, and understand the physics of high-frequency acoustic scattering from controlled, laboratory-generated microstructure, with a focus on double diffusion. The initial development of simple physics based scattering models is a secondary objective of this work.

## APPROACH

The approach taken here to understanding acoustic scattering from different types of oceanic microstructure involves extensive laboratory experiments aimed at determining the dominant scattering mechanisms and at refining existing scattering models or guiding the initial development of new scattering models.

Oceanic microstructure refers to small-scale physical processes that give rise to gradients in temperature and salinity, and thus in oceanic density and sound speed. These fluctuations in the medium material properties result in the scattering of high-frequency sound. There is growing evidence suggesting that turbulent oceanic microstructure can be a significant source of high-frequency acoustic scattering, as significant as that from other naturally occurring sources with similar spatial scales (Seim et al., 1995; Moum et al., 2003; Ross and Lueck, 2003; Warren et al., 2003). However, very little is known regarding the scattering of high-frequency sound double-diffusive microstructure.

In the ocean there are two manifestations of double-diffusive microstructure (Schmitt, 1994): the salt-finger regime, in which both temperature and salinity decrease with increasing depth, and the diffusive regime of double diffusion, in which both temperature and salinity increase with depth. An extensive set of laboratory experiments focused on understanding high-frequency acoustic scattering from the diffusive regime of double diffusion has been completed. Large regions of the Arctic (Neal et al., 1969) and Antarctic (Muench et al., 1990) oceans are susceptible to this type of microstructure,

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**30 SEP 2005** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2005 to 00-00-2005** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Laboratory Measurements of Multi-Frequency and Broadband Acoustic Scattering from Turbulent and Double-Diffusive Microstructure** | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Woods Hole Oceanographic Institution,Applied Ocean Physics and Engineering Department,Bigelow 211, MS #11,Woods Hole,MA,02543** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES
**code 1 only**

14. ABSTRACT
**The long-term goal of the proposed research is to develop a fundamental understanding of high-frequency acoustic scattering from small-scale physical processes that occur in the ocean interior.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **15** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

though different regions may exhibit diffusive-convective layers at different depths. In the ocean, the diffusive-convective instability often results in thermohaline staircases with multiple well-mixed layers separated by thin interfaces. It is thought that diffusive-convective layers, and in particular the associated fluxes, may play an important role in high-latitude watermass formation, which in turn may be an important element in the global climate system (Kelley et al., 2003). High-frequency broadband acoustic scattering techniques may allow these thermohaline staircases to be imaged rapidly and remotely, providing a means to remotely determine their spatial extent, a means to investigate the formation and evolution of thermohaline staircases, and a means to remotely investigate layer thickness, a parameter needed for determining vertical double-diffusive fluxes (Kelley, 1986).

An acoustic scattering laboratory has been constructed to measure high-frequency broadband acoustic scattering from double-diffusive microstructure. In the laboratory, a single sharp double-diffusive interface can be generated that separates warm, salty (and dense) water in the lower layer, from cold, fresh water in the upper layer (Fig. 1). The upper layer is cooled from above and the lower layer is heated from below to provide the necessary heat fluxes to maintain the double-diffusive system. As the molecular diffusion of heat is 100 times faster than the molecular diffusion of salt, adjacent parcels of water can come into thermal equilibrium while significant salinity gradients remain. The salt distribution maintains the gravitational stability of the system and allows any given interface to be maintained for various weeks in the laboratory, while the faster diffusion of heat across the interface drives convection in the adjacent mixed-layers. It is then possible to measure high-frequency broadband acoustic scattering from the sharp double-diffusive interface that separates the upper and lower mixed-layers. Controlled laboratory experiments have been performed in which the frequency, waveform, range, beam parameters, and physical parameters governing the microstructure are known or measured. The experiments are principally in the backscatter configuration, although some forward scattering measurements have also been performed. The acoustic scattering measurements are supplemented by direct optical shadowgraph observations of the double-diffusive interfaces, and by direct temperature and conductivity microstructure measurements using fast response thermistors and 4-electrode conductivity cells. The power of broadband acoustics is exploited fully in the subsequent data analysis, both by looking at the frequency response of the scattering from the interface and using pulse compression techniques to increase the spatial resolution of the measurements.

## WORK COMPLETED

The laboratory for performing scattering measurements from double-diffusive microstructure was completed in the first year of this the project, and subsequently six experiments, each 2-3 weeks in duration, have been completed over the course of almost two years. The analysis of these data is now complete and two manuscripts are in preparation (Lavery and Ross, Ross and Lavery, in prep.).

The typical evolution of the upper and lower mixed-layer temperature and salinity are shown in Fig. 2. High-frequency broadband (200-300 kHz and 350-650 kHz) acoustic backscattering measurements were performed at various ranges, concentrating on a range of .75 meters, and over a range of values for the mixed layer temperature and salinity. As the range-dependence of the scattered pressure is complex, the results are presented in terms of the ratio of the scattered pressure at the receiver and the pressure incident at the interface, $P_{scat} / P_{inc}$, which is a function of range. Due to the limited physical size of the tank, the range dependence of the scattered returns could not be established. The

size of the acoustic footprint at the interface for the ranges used span the first three Fresnel zones, and the spatial scale of the interface "roughness" appears to lie somewhere between the acoustic wavelength and the size of the acoustic footprint. Thus, a bi-static approach was taken, in which the transmit and receive transducers were placed as close as possible to a monostatic backscattering configuration during data acquisition. The benefit of this setup is that it allows a simple "calibration" of the system to be performed, in which the transmit and receive transducers were separated and placed facing each other at a known range, thus allowing the pressure incident at the interface to be measured directly. Calibrations using a 20 mm diameter Tungsten Carbide standard target were also performed.

**RESULTS**

It has been found that the double-diffusive system is highly dynamic, with strong fluxes, convection cells, and turbulent plumes, giving rise to a complex scattering environment. These experiments have demonstrated that acoustic scattering techniques are a highly sensitive tool for studying double-diffusive interfaces, where other more conventional tools, such as microstructure probes or optical shadowgraph techniques, suffer from problems relating to probing inappropriate spatial and time scales. The information obtained from the shadowgraph images was inadequate to investigate the small-scale physics of the interface as it integrates over the optical index of refraction of the water across the entire tank (approximately 1 meter wide). In contrast, the microstructure probes provide detailed vertical spatial information about the double-diffusive interface, but provide no information on the horizontal or temporal scales of variability, as well as being a highly invasive tool. Typically, 20-30 minutes elapsed between the time microstructure probes were dropped through the interface and the measured acoustic signals returned to their original levels. Specific results of the high-frequency broadband acoustic scattering measurements from double-diffusive interfaces include:

<u>Determination of dominant scattering mechanisms</u> (Fig. 3)
Analysis of the frequency dependence, or spectral response, of ping-by-ping echo returns from double-diffusive interfaces has revealed that there are two general types of returns: most returns exhibit relatively little structure at the frequencies investigated, while a minority of the returns (25-50%) exhibit a clear interference pattern with peaks and nulls that are consistent with scattering from a three-layered double-diffusive system with returns from two primary interfaces.

Intermittent "events" resulting in elevated scattering levels were observed on time scales of approximately 3-5 minutes. During these elevated scattering periods, the echo returns rarely exhibited the peaks and nulls that are consistent with an interference patterns due to scattering from two primary interfaces. Possible causes for these "events" is elevated turbulence either from the passage of waves on the surface of the interface, which were observed with the shadowgraph system, or turbulent plumes migrating across the acoustic beam. Such plumes have been observed in other laboratory studies of double-diffusive phenomena (Kelley, 1986), though they were not observed here, possibly because of the integration volume of the shadowgraph system.

Pulse compression techniques (Chu and Stanton, 1998) were used to increase the spatial resolution with which the double-diffusive interfaces were observed. The time-domain resolution of the pulse compression output is equal to 1/B (B=bandwidth), and the processing gain (output SNR to input SNR) is proportional to 2BT (T=pulse length). Using PC techniques, the individual returns that showed a spectral response characteristic of an interference pattern typically showed two main peaks

in the pulse compression output (though occasionally there were more than two peaks). However, many returns that did not exhibit much spectral structure had more than one peak in the pulse compression return, a result of the increased processing gain and spatial resolution.

Remote measurement of interface thickness (Fig. 4)
Due to the increased spatial resolution provided by pulse compression techniques, as well as increased processing gain, it was possible to more accurately and reproducibly determine the interface thickness from the peaks in the pulse compression output. Interface thickness is defined here as the spatial separation between the two largest peaks in the pulse compression output, larger than the pre-determined signal processing side-lobes. Such measurements of interface thickness are in good general agreement with the measurements performed with the microstructure sensors, as well as with the shadowgraph images, though the interface thickness inferred from the shadowgraph images appears to be consistently smaller.

The temperature in the upper and lower mixed layers was typically controlled so as to maintain a constant density ratio ($\approx 4$). The interface thickness did not appear to vary significantly over the course of the experiment, suggesting that the density ratio is more important in determining the interface thickness than the temperature and salinity differential across the interface, though it is necessary to have temperature and salinity differences to maintain an interface and to give rise to scattering.

Dependence of mean scattering levels on physical parameters (Fig. 5)
The mean amplitude of $P_{scat}/P_{inc}$ decreased with time as a result of the decreasing temperature and salinity differentials across the double-diffusive interface, though the variability remained large throughout the duration of all experiments. The time scale of the variability seemed well correlated to the inverse buoyancy frequency.

The importance of forcing in determining acoustic variability (Fig. 6)
The importance of the forcing, or the heating of the lower layer and cooling of the upper layer to maintain a large temperature differential across the interface, in determining the time-scales of variability was clearly illustrated during the February 2005 experiment in which the forcing was removed and the evolution of the double-diffusive interface monitored acoustically. Within 10 minutes of the removal of the forcing, the short time-scale acoustic variability disappeared.

Temporal evolution of multiple double-diffusive interfaces (Fig. 7)
During the February 2005 experiment, multiple double-diffusive steps were created and their evolution was observed acoustically. The merging of multiple double-diffusive steps was observed, an accomplishment that could not be performed with the same temporal or spatial resolution with the shadowgraph system, which had limited vertical range, or with the highly invasive microstructure instrument, which could only be plunged every 20-30 minutes, as it seriously disrupted the interface.

Development of an acoustic scattering model for turbulent oceanic microstructure
An acoustic scattering model for turbulent oceanic microstructure has been developed that includes the effects of density fluctuations, which had been ignored in previously models (Lavery et al., 2003). This models shows that acoustic scattering from turbulent microstructure can be significantly stronger than was generally thought in areas of strong salinity stratification.

## IMPACT/APPLICATIONS

A common misconception in the ocean research community is that high-frequency acoustic scattering in the water-column is dominated by biological organisms. Only recently has it become more accepted that turbulent oceanic microstructure can also cause significant scattering levels, under certain circumstances. This study has shown that high-frequency acoustic scattering from turbulent oceanic microstructure can be even stronger that was generally believed in regions with strong salinity stratification. In addition, this study has shown that double-diffusive microstructure can also be an important contributor to water-column scattering. This research has also illustrated the importance of scattering from double-diffusive microstructure on signal coherence. Ultimately, this research may also allow high-frequency acoustic scattering techniques to become a useful remote sensing tool to synoptically characterize and map the spatial and temporal distributions of oceanic microstructure. For example, using the results of the experiments performed on double-diffusive interfaces as a framework, it may be possible to rapidly and remotely determine interface thickness at locations in which double diffusion manifests itself in the ocean as a series of staircases in which well-mixed layers are separated by double-diffusive interfaces, such as in the Arctic or Antarctic.

## RELATED PROJECTS

- Andone Lavery has received internal funding from WHOI to determine the extent to which multiple single frequency volume backscattering data from the Gulf of Maine can be used to discriminate between regions in which the scattering is dominated by turbulent microstructure and zooplankton. Regions of interest include internal waves propagating onto Georges Bank, for which the contribution to scattering from microstructure is expected to be elevated.

- 2005 Summer Student Fellow, Yue Li, investigated the origin of thin scattering layers observed in 2002 in the western Antarctic Peninsula, a region susceptible to double diffusion. Scattering at multiple single-frequencies, high-resolution microstructure data, video plankton recorder data, and direct biological sampling using MOCNESS tows were available at times and locations at which the thin scattering layers were observed. Though this study is still ongoing, preliminary results suggest that the observed scattering layers may be due, at least in part, to double diffusion.

## REFERENCES

Chu, D., and Stanton, T. K. "*Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton,*" J. Acoust. Soc. Am. **104**(1), 39-55, (1994).

Kelley, D. E., Fernando, H. J. S., Gargett, A. E., Tanny, J., and Ozsoy, E. "*The diffusive regime of double-diffusive convection*," Progress in Oceanography **56**, 461-481, (2003).

Lavery, A. C., Schmitt, R. W., and Stanton, T. K. "*High-frequency acoustic scattering from turbulent oceanic microstructure: the importance of density fluctuations,*" J. Acoust. Soc. Am. **114(5)**, 2685-2697, (2003).

Lavery, A. C., and Ross, T. "*High-frequency acoustic scattering from double-diffusive microstructure: Determination of dominant scattering mechanism,"* in preparation for J. Acoust. Soc. Am.

Moum, J.N., Farmer, D. M., Smyth, W. D., Armi, L., Vagle, S. "*Structure and generation of turbulence at interfaces strained by internal solitary waves propagating shoreward over the continental shelf*," J. Phys. Oceanogr. **33**, 2093-2112, (2003).

Muench, R. D., Fernando, H. J. S., and Stegan, G. R. "*Temperature and salinity staircases in the northwestern Weddell Sea,*" J. Phys. Oceanoghr. **20**, 295-306, (1990).
Neal. V. T., Neshyba, S., and Denner, W. "*Thermal stratification in the Arctic Ocean*," Science **166**, 373-374, (1969).

Schmitt, R. W. "*Double Diffusion in Oceanography*," Annu. Rev. Fluid. Mech. **26**, 256-285, (1994).
Kelley, D. "*Oceanic thermohaline staircases,*" Ph.D. Thesis, Dalhousie University, 1986

Ross, T., and Lavery, A. C. "*On the acoustic remote sensing of double-diffusive interfaces in the ocean: Laboratory observations of interface evolution and thickness*," in preparation for J. Geophys. Res. - Oceans.

Ross, T., and Lueck, R. "*Sound scattering from oceanic turbulence*," Geophys. Res. Lett. **30**(6), 1344, (2003).

Seim, H.E., Gregg, M.C. Miyamoto, R.T. "*Acoustic backscatter from turbulent microstructure,*" J. Atmos. Ocean. Technol. **12**(2), 367-380, (1995).

Warren, J.D., Stanton, T.K., Wiebe, P.H., Seim, H.E. "*Inference of biological and physical parameters in an internal wave using multiple-frequency, acoustic-scattering data,*" ICES J. Mar. Sci. **60**(5), 1033-1046, (2003).

**PUBLICATIONS**

<u>Lavery</u>, A. C., Schmitt, R. W., and Stanton, T. K. (2003). "*High-frequency acoustic scattering from turbulent oceanic microstructure: the importance of density fluctuations*," JASA 114(5), 2685-2697 [Published, refereed].

<u>Lavery</u>, A.C., Stanton, T.K., and Wiebe, P.H. (2002). "*Variability in high-frequency acoustic backscattering in the water-column*," in "Impact in Littoral and Environmental Variability on Acsoutic Predictions and Sonar performance," editors N. G. Pace and F. B. Jense, Kluwer Academic Publishers, pp. 63-70 [Published].

<u>Lavery</u>, A.C., Benfield, M.C., Wiebe, P.H., and Stanton, T.K. (2004). "*High-frequency acoustic volume backscatter in the upper water column: imaging zooplankton and microstructure*," Proceedings of the Seventh European Conference on Underwater Acoustics (ECUA2004), Delft, The Netherlands, editor D.G. Simmons, Volume 1, pp. 351-361[Published].

**POSTDOCTORAL FELLOWS ASSOCIATED TO THIS PROJECT**

Tetjana Ross, WHOI Postdoctoral Fellow, September 2003 – April 2005. Now faculty at Dalhousie University, Canada.

## PRESENTATIONS ASSOCIATED TO THIS PROJECT

Lavery, A.C. "*High-frequency broadband acoustic scattering from double-diffusive interfaces*", Physical Oceanography Bouy Seminar, September 2005 (invited)

Ross, T. and Lavery, A. C. "*Laboratory observations of sound scatter from double-diffusive interfaces*", DIALOG VII, November 2004

Lavery, A .C. "*Laboratory measurements of multi-frequency and broadband acoustic scattering from turbulent and double-diffusive microstructure*," ONR Site Review, WHOI, September 2004

Lavery, A. C., Benfield, M.C., Wiebe, P.H., and Stanton, T.K. "*High-frequency acoustic volume backscatter in the upper water column: imaging zooplankton and microstructure*," Proceedings of the Seventh European Conference on Underwater Acoustics (ECUA2004), Delft, The Netherlands, July 2004

Lavery, A.C. "*High-frequency acoustic scattering from microstructure and zooplankton*", AGU Oceans Sciences Meeting, Portland Oregon, January 2004(invited)

Lavery, A.C. "*High-frequency acoustic imaging of microstructure and zooplankton*", WHOI SSF Lecture Series, June 2003

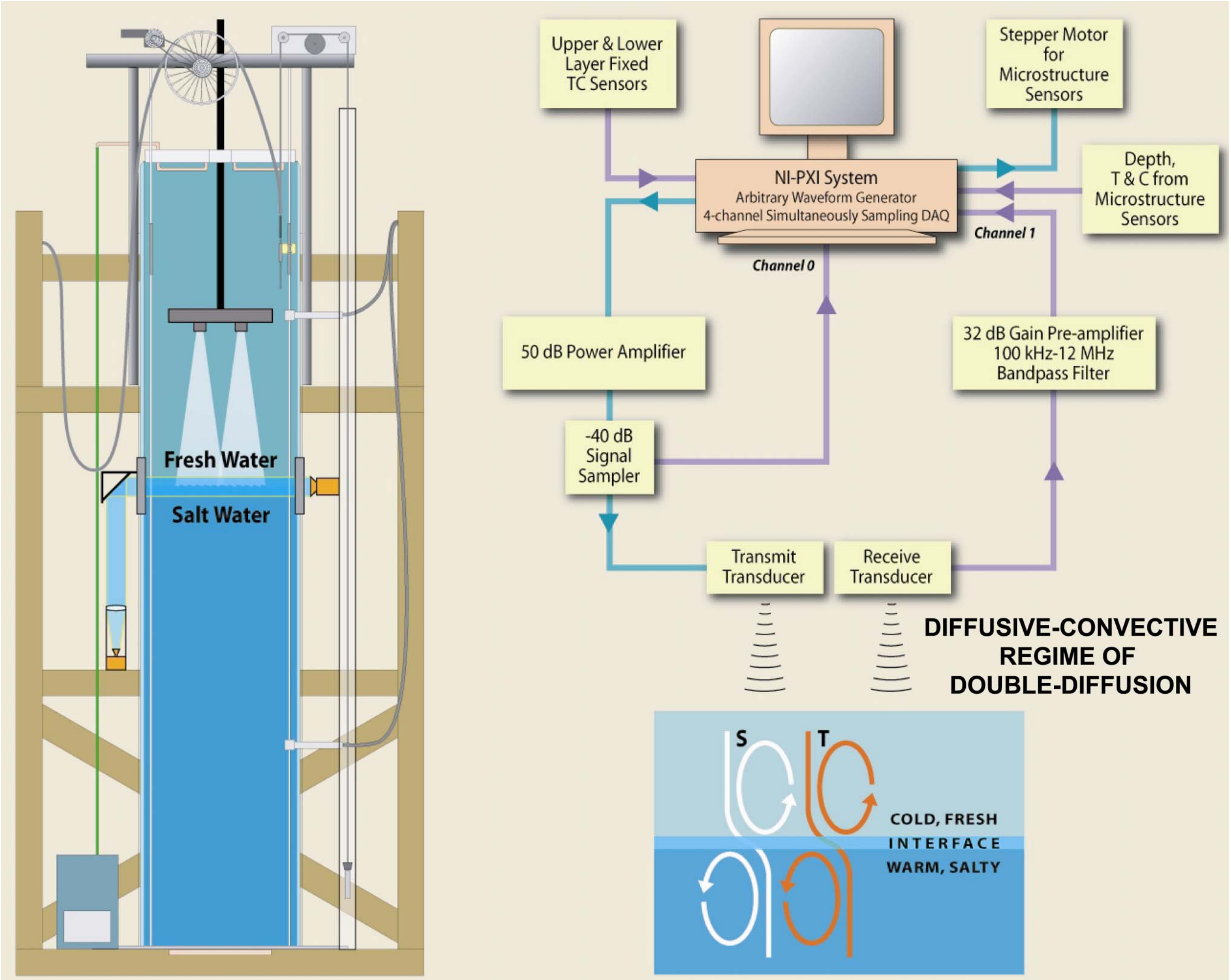


***Figure 1. Schematic showing the laboratory constructed for measuring high-frequency broadband (200-300 kHz and 350-650 kHz) acoustic scattering from the diffusive regime of double diffusion. The lower mixed-layer is filled with warm, salty (and dense) water, and the upper layer is filled with cold, fresh water: a sharp interface separates the mixed layers. A shadowgraph system was built to obtain optical images of the interface, and small-scale temperature and conductivity measurements were performed using a fast-response thermistor and four-electrode conductivity probe. The tank is approximately 4.6 meters deep and 1 meter wide. Two fixed temperature and conductivity sensors are mounted in the upper and lower mixed-layers, providing continuous monitoring on the mixed layer properties. A box diagram of the data acquisition system used to collect the acoustic and ancillary data is shown.***

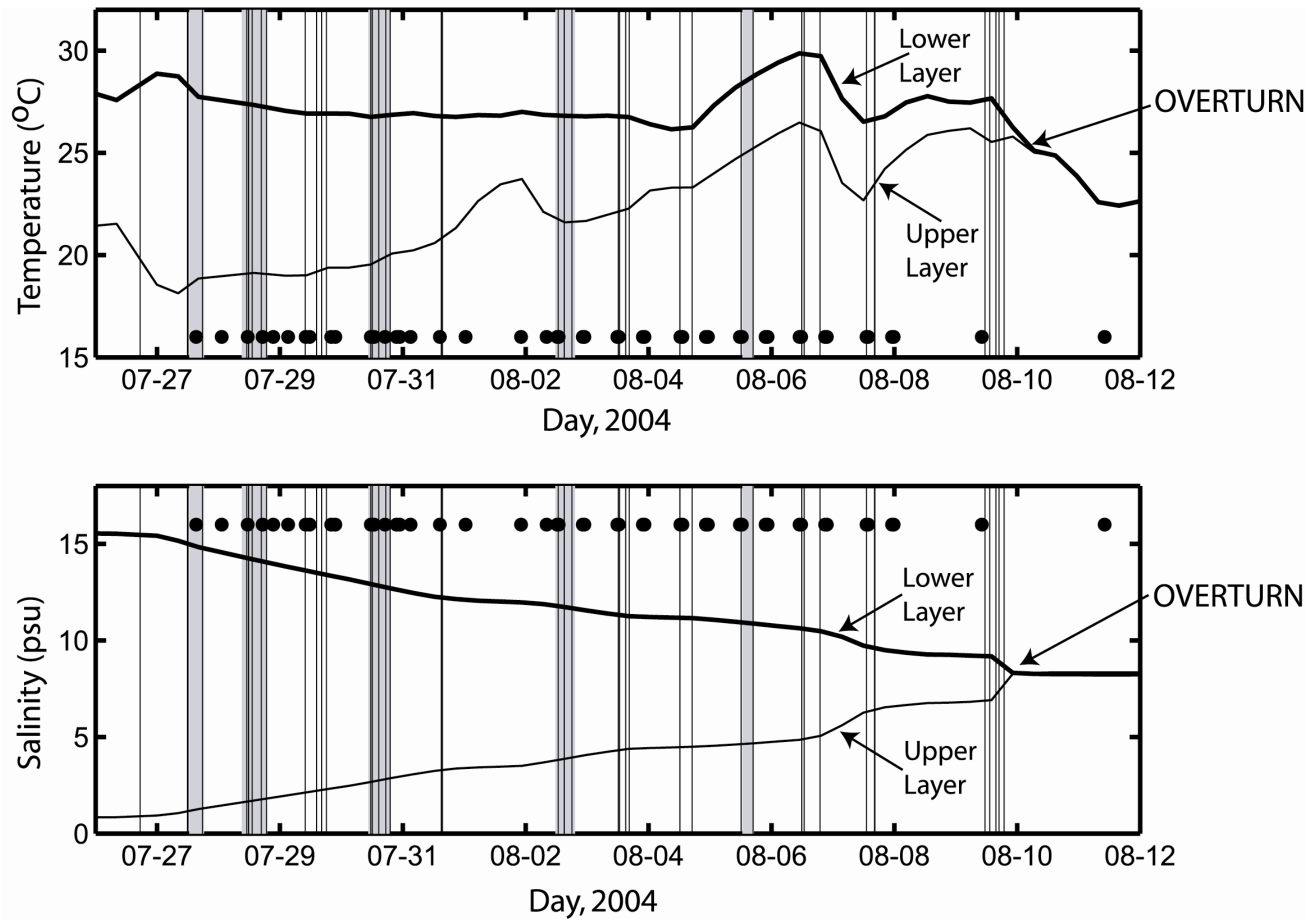


***Figure 2. Six experiments involving high-frequency broadband acoustic scattering from sharp double-diffusive interfaces, each 2-3 weeks in duration, have been completed over the course of the last two year. The evolution of the temperature and salinity in the upper and lower mixed layers, as measured by two fixed CT sensors mounted in the upper and lower layers is shown here for the experiment conducted in late July and early August, 2004. The vertical lines shown the times at which direct microstructure plunges were performed (37 plunges total for this particular experiment). The vertical gray shaded regions show the times at which digital movies of the interface were taken using the shadowgraph system. The black circles represent the times at which broadband acoustic data were collected.***

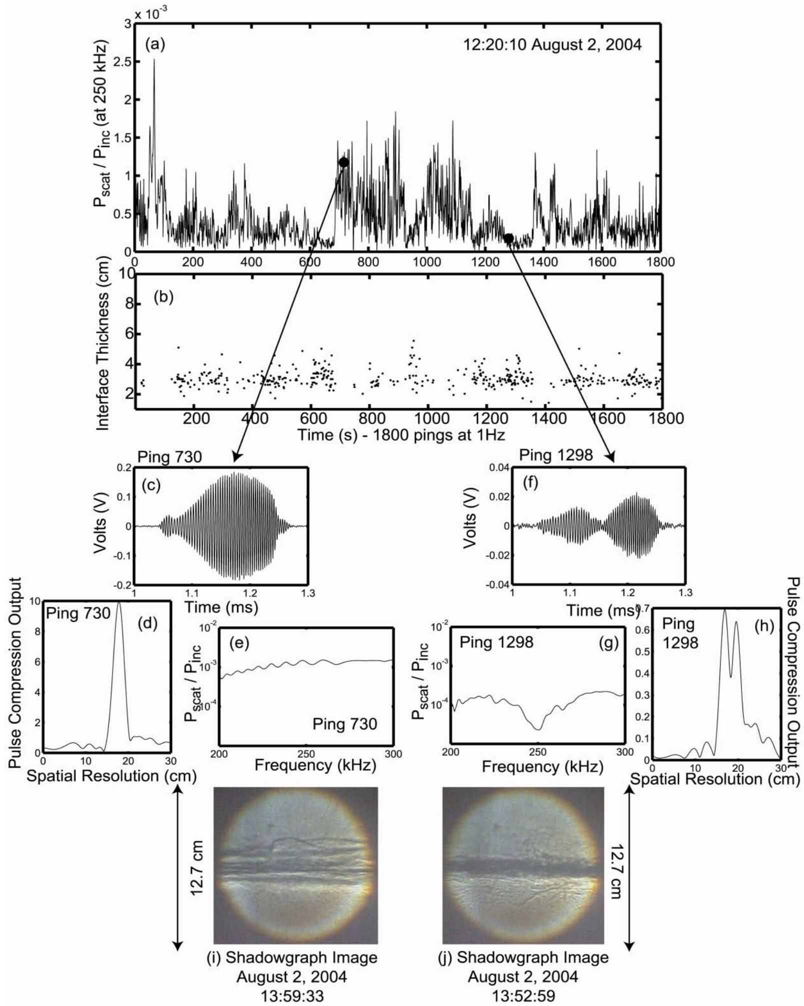


***Figure 3. (a) $P_{scat}/P_{inc}$ at 250 kHz as a function of time for 1800 individual pings collected at a 1 Hz sampling rate on August 2, 2004. The scattered pressure from the double-diffusive interface was highly variable, with intermittent events occurring on 3-5 minute time scales during which the scattered pressure increased by more than an order of magnitude, and exhibited a different spectral response to the scattered pressure measured when an intermittent elevated scattering event was not observed. (b) Interface thickness as function of time, as calculated from the two largest peaks in the pulse compression output. (c) Raw echo return, (d) spectral response, and (e) pulse compression output for an individual echo return from the double-diffusive interface during an intermittent elevated scattering event. (f) Raw echo return, (g) spectral response, and (h) pulse compression output for an individual echo return from the double-diffusive interface when an intermittent elevated scattering event was not observed. (i) Shadowgraph image showing what appears to be a relatively turbulent interface with an "event" that looks like the passage of a wave, and (j) a shadowgraph image of what appears to be a calmer interface in which the interface thickness can be clearly determined.***

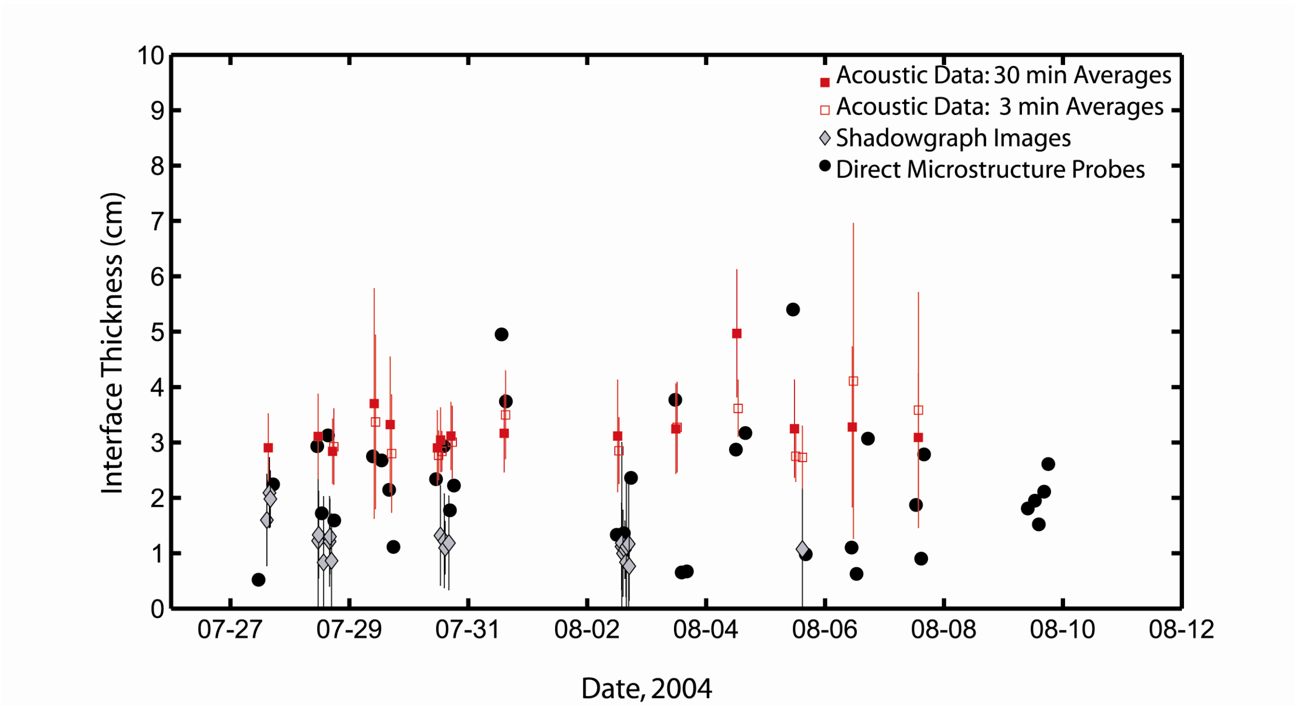


***Figure 4. Evolution of the interface thickness during the July and August, 2004, experiment. The interface thickness is estimated from (i) the individual frames of the shadowgraph digital movies (gray diamonds represent an average for each 1 minute movie), (ii) the conductivity microstructure probes (black circles), (iii) from the separation in the two largest peaks (above the threshold set for processing side-lobes) in the pulse compression output (full red squares represent averages over 1800 individual returns sampled at 1 Hz, and empty red squares represent averages over 1800 individual returns sampled at 0.1 Hz). The error bars corresponds to one standard deviation. The interface thickness as calculated from the shadowgraph images consistently estimated smaller interface thickness than either the acoustics or direct microstructure probes, and this is thought to arise from complications in the definition of interface thickness from the shadowgraph images.***

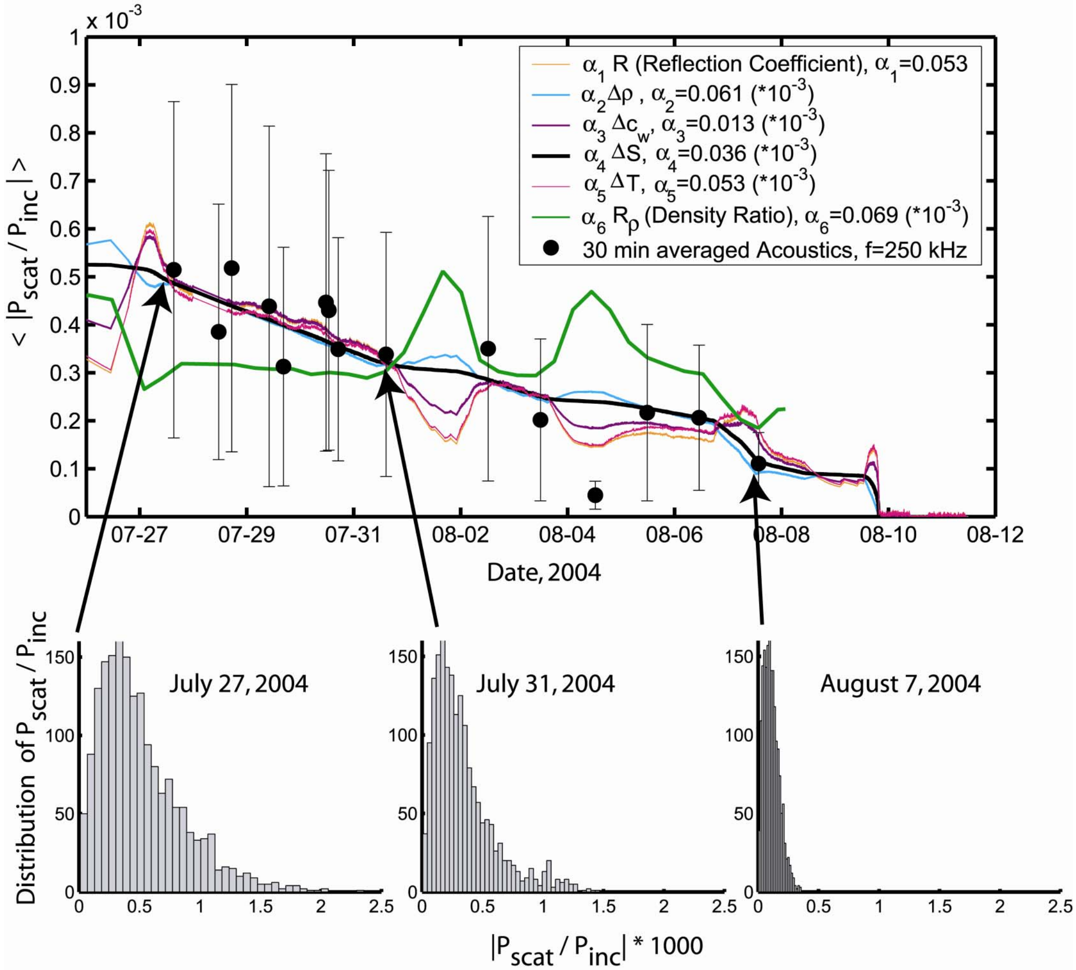


***Figure 5. Mean amplitude of $P_{scat}/P_{inc}$ at 250 kHz (black circles, error bars represent a standard deviation) during the July and August, 2004, experiment. The averages were only performed for acoustic data files that were at least 30 minutes in duration, to assure that multiple intermittent scattering events were probed during each data acquisition period. A least-squared fit was preformed to obtain the best fit scaling parameter $\alpha_{1\text{-}6}$ between the mean $P_{scat}/P_{inc}$ at 250 kHz and the following parameters: the reflection coefficient, R (orange line), density step, $\Delta\rho$ (blue line), sound speed step, $\Delta c_w$ (purple line), salinity step, $\Delta S$ (black line), temperature step, $\Delta T$ (pink line), and density ratio, $R_\rho$ (green line), as calculated from the CT sensors in the upper and lower mixed-layers were. The resulting scaling parameters are shown in the legend. The best fit was obtained for the difference in the salinity between the upper and lower mixed layers. The histograms show the distribution of the amplitude of $P_{scat}/P_{inc}$ at 250 kHz for three individual 30 minute long data acquisition periods.***

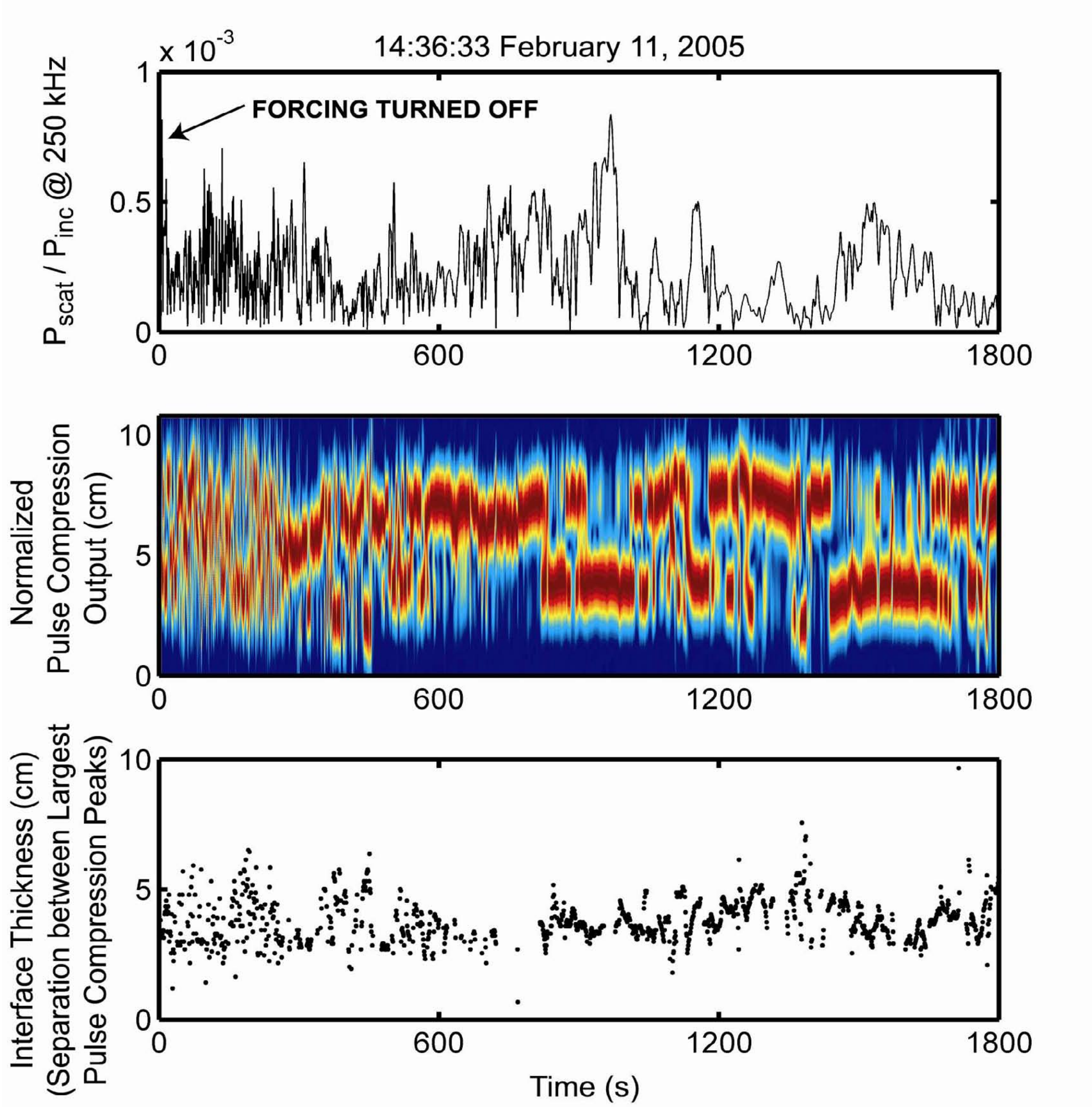


***Figure 6. (a) $P_{scat}/P_{inc}$ at 250 kHz as a function of time for 1800 individual pings collected at a 1 Hz sampling rate during the February 2005 experiment. The forcing was turned off at the beginning of this data acquisition period, that is the heating and cooling of the upper and lower mixed-layers was removed. (b) Normalized pulse compression output for the same data acquisition period. It can be seen that the time scale of variability changes significantly with the removal of the forcing, though it takes approximately 10 minutes for the interface to equilibrate. It can be seen from the main peak in the pulse compression analysis occurs at a relatively random position while the forcing is still active, but once the forcing is removed the main peak in the pulse compression output is more coherent from ping to ping. (c) The interface thickness, defined as the separation between the two largest returns in the pulse compression output, is shown here. Only some echo returns exhibit more than one peak in the pulse compression. As the forcing is removed and the interface equilibrates, the interface thickness becomes more coherent over longer time scales.***

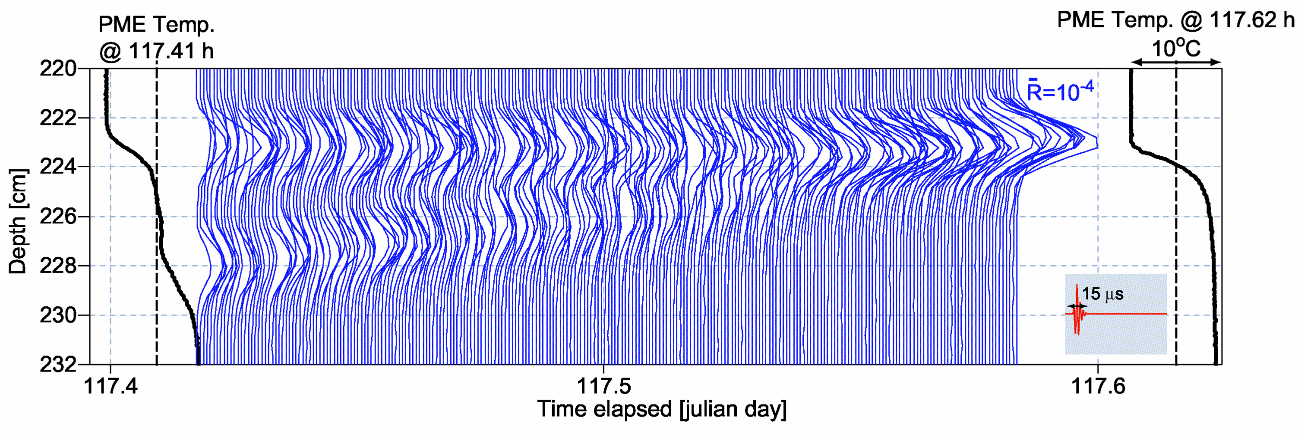


***Figure 7. Using high-frequency broadband acoustic scattering returns it is possible to observe the evolution and dynamics of multiple double-diffusive interfaces. Shown here is the merging of two double-diffusive steps ($P_{scat}/P_{inc}$) as a function of time and depth. A 15 μs long chirp, 200-300 kHz, was used. Temperature profiles (black lines) obtained with the microstructure instruments are shown to the left and right of the acoustic data.***